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Fire Behavior and Risk Analysis in Spacecraft

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FIRE BEHAVIOR AND RISK ANALYSIS IN SPACECRAFT

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ABSTRACT

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Practical risk management for present and future spacecraft, including space stations, involves the optimization of residual risks balanced by the spacecraft operational, technological, and economic limitations. Spacecraft fire safety is approached through three strategies, in order of risk: (1) control of fire-causing elements, through exclusion of flammable materials for example, (2) response to incipient fires through detection and alarm, and (3) recovery of normal conditions through extinguishment and cleanup. Present understanding of combustion in low gravity is that, compared to normal-gravity behavior, fire hazards may be reduced by the absence of buoyant gas flows yet at the same time increased by ventilation flows and hot particle expulsion. This paper discusses the application of low-gravity combustion knowledge and appropriate aircraft analogies to fire detection, fire fighting and fire-safety decisions for eventual fire-risk management and optimization in the spacecraft.

INTRODUCTION

Fire is one of the most feared hazards in spacecraft, just as it is in aircraft and boats. Not only does fire threaten the occupants with the obvious dangers of heat, toxic gases, and structural failure, but it also can affect the crew and the mission integrity and effectiveness in subtle ways. Extinguishment as well as combustion by-products can contaminate the spacecraft breathing atmosphere. False alarms from sensitive sensors, strict limitations on acceptable materials, and stringent high-safety-factor operating procedures all can restrain useful activities in space missions.

Risk management encompasses the identification, elimination, and control of hazards. In space missions, just as in other human endeavors, total elimination of hazards is impossible. Thus, fire-safety strategies aim to optimize risk levels by reducing hazards to a minimum while recognizing the operational, technological, and economic restraints on spacecraft fire safety (Percy and Raasch, 1986, Rodney, 1987).

Present spacecraft fire-safety procedures are adequate, to the extent of the limited knowledge of fire behavior in the milieu of space. Extended mission schedules and unique features of future spacecraft concepts, however, will make more demands on fire safety. The primary emphasis of the paper is on the U.S. Space Station Freedom, which is a permanent orbiting habitat, laboratory, and workshop that is expected to operate within a decade. Freedom incorporates varied and complex structures, carries a crew of differing skills, accommodates scientific, manufacturing, and housekeeping activities, and serves as a self-contained community with rescue many days away (DeMeis, 1986).

Percy et al. (1985a) undertook a study of risk management and safety trade-offs for the baseline designs of a U.S. space station. Many potential threats to crew safety were considered in the study, although fire was of particular concern. The output of this study included a list of literature references on spacecraft crew safety up to 1984 (Percy et al. 1985b). A subsequent, independent review of the needs of fire safety in advanced spacecraft led to a meeting held at the NASA Lewis Research Center in August 1986, which provided research and technology recommendations to define studies in spacecraft fire safety, some of which are currently underway (Friedman and Sacksteder, 1987, Youngblood and Seiser, 1988).

The purpose of this paper is to review the assumptions and knowledge influencing spacecraft fire safety and its management, drawing on past results and present studies and designs. An approach to spacecraft fire-risk analysis encompasses three study themes: (1) the acquisition of fundamental science knowledge to reduce gaps in required information, (2) the adaptation of this knowledge into practice for spacecraft safety, and (3) the formulation of risk acceptance and mitigation decisions (Rodney, 1987, Raasch et al. 1985). This paper covers the theme of fundamental science knowledge by discussing combustion in the reduced-gravity environment of spaceflight. The reduction of gravity-induced buoyant flows has a profound effect on flammability and flame spread;

indeed fires may be inhibited or enhanced in micro-gravity, depending on particular conditions (Friedman and Sacksteder, 1987, Friedman, 1987). The paper then reviews the adaptation of spacecraft and analogous fire-safety knowledge by describing the techniques for spacecraft fire detection and fire control. Finally, the paper covers the theme of risk decisions by expanding the review of techniques to include those potential problems in future spacecraft that can influence fire-safety strategies. A concluding section of the paper surveys specific needs and relevant research underway for an important future mission, the Space Station Freedom.

SPACECRAFT FIRE-SAFETY STRATEGIES

The confined quarters, limited atmospheric and fire-fighting resources, lack of external rescue capability, and the poorly understood effects of the microgravity environment make the hazard of fire extremely dangerous in spacecraft. Risk management must combat this threat by optimizing risk levels within the constraints of practicality, technology, and costs. A spacecraft safety policy must proceed through steps of identification of hazards, analysis of their significance, and decisions to alleviate their impact (Rodney, 1987).

The necessary elements for fire are the presence of fuel, ignition, and oxygen. These ingredients are illustrated in Fig. 1, which presents the elements in the form of the familiar fire "triangle" and shows some examples of hazards encountered in spacecraft and their controls. Obviously, safety can be guaranteed by the absolute exclusion of one of the three elements. In spacecraft, exclusion is approached through elimination of potential ignition sources by design and safety procedures and through elimination of potential fuels by material screening. The NASA Handbook NHB 8060.1B (Flammability, Odor, etc., 1981) states that, for unrestricted use in spacecraft, materials must burn for less than 15 cm (6 in.) upward with a burning time not to exceed 10 min, when exposed at the bottom edge to an ignition source in the most hazardous atmosphere anticipated in service. Materials failing this test may be used only after further screening in downward burning tests and then used only in configurations where, by analysis and testing, flame-propagation paths and ignition sources are eliminated.

In practice, this exclusion of fire-causing elements cannot be assured for several reasons. First, knowledge and experience concerning fire behavior in the low-gravity space environment is very limited. (This, of course, is a major subject of review in this paper.) Even the rigorous material acceptance standards of NHB 8060.1B are based on tests necessarily conducted under ordinary Earth-gravity conditions, and the fire resistance of approved materials under space conditions is not generally predictable. Second, a realistic safety program must recognize the possibility of "breakdowns," that is, the waivers of non-approved materials, unexpected ignition sources, and leakage of oxidant into inerted volumes. Last, some fire elements may need to be accepted onboard spacecraft in order to allow certain necessary and useful activities.

Fire-safety strategies for spacecraft are illustrated by the relationship of concepts shown in Fig. 2. The three concepts of control, response, and recovery each represent an increasing level of risk acceptance, in the order named. The lowest-risk tactic of control incorporates the design strategies proposed by Percy and Raasch (1986) as "design to

preclude" and "design to control." This is a first line of defense, involving the exclusion or at least the minimization of fire-causing elements. Practical approaches in this strategy can include spacing and storage requirements for necessary flammables, safety factors to reduce ignition-causing energy releases, and atmospheric inerting procedures for noninhabited compartments. The higher-risk tactic of response recognizes a low probability of the initiation of a fire. The general NASA fire-prevention principle applicable in this instance is to assume ignition but require that the resulting fire be self-extinguishing within a short distance (LeDoux, 1987). Thus the response strategy involves overheat and fire detection, alarm systems, automated fire suppression, and fire-barrier designs, as examples. The highest-risk tactic of recovery recognizes the lower but finite probability of an established fire during long-duration space missions. The recovery strategy involves crew training for fire fighting, extinguishment procedures for entrenched fires, fire-damage control, and atmospheric cleanup, as examples. A complete program of spacecraft fire safety must encompass all three strategies illustrated in Fig. 2, providing for recovery procedures even if adequate fire-control and response procedures are established.

Inherent in the fire-safety strategies, as proposed, is the question of the desirable degree of safety. The spacecraft safety philosophy of Percy and Raasch (1986) offers a baseline option for safety, where the planned worst-case occurrence would cause no human injury but may damage an orbiting spacecraft to the extent that some operations are temporarily suspended. The application of philosophy to the Freedom space station is hardly straightforward; however, the safety review of Rodney (1987) implies that this degree of risk acceptance underlies the program planning logic. It is interesting to note the other possibilities for safety directions proposed by Percy and Raasch. The most risk-free option is the complete avoidance of physical damage. The greatest-risk option is the anticipation of a serious fire, requiring crew evacuation and abandonment of an orbiting spacecraft.

It is not yet possible to identify all the quantitative factors that enter into the philosophy of risk strategies for orbiting spacecraft such as Freedom. Instead, this paper presents information that may contribute eventually to these risk-management decisions. The key determinations must account for the balance between the needs for useful and practical functions in space and the productivity restrictions imposed by safety procedures to lower the risk of fire.

COMBUSTION AND FIRE IN SPACE

The Space Environment

On Earth it has long been understood that gravitationally induced buoyancy dominates the spread of fires. The placement of fire detectors in ceiling locations, for example, anticipates the predictable upward bulk motion of combustion products in normal gravity. Now, as a practical matter, the testing of spacecraft fire-safety technology, including fire detection and intervention equipment as well as material-flammability screening, must generally be performed in ground-based facilities where, in contrast to the use environment, buoyant motion dominates. Thus the planning for adequate levels of safety in spacecraft requires not only an understanding of the low-gravity, fire-related behavior of

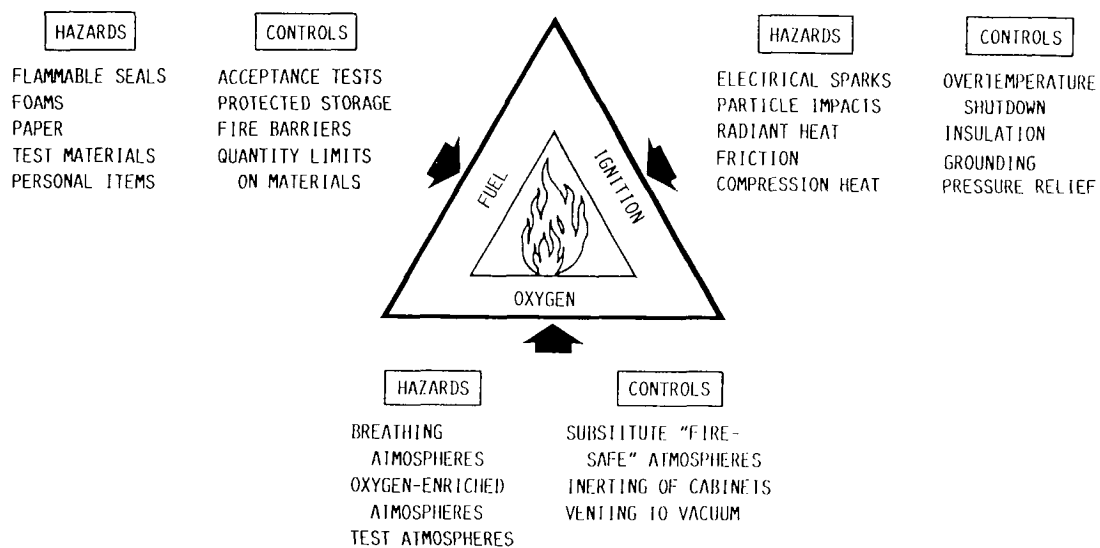


FIGURE 1. - EXAMPLES OF COMMON FIRE CAUSES IN SPACECRAFT.

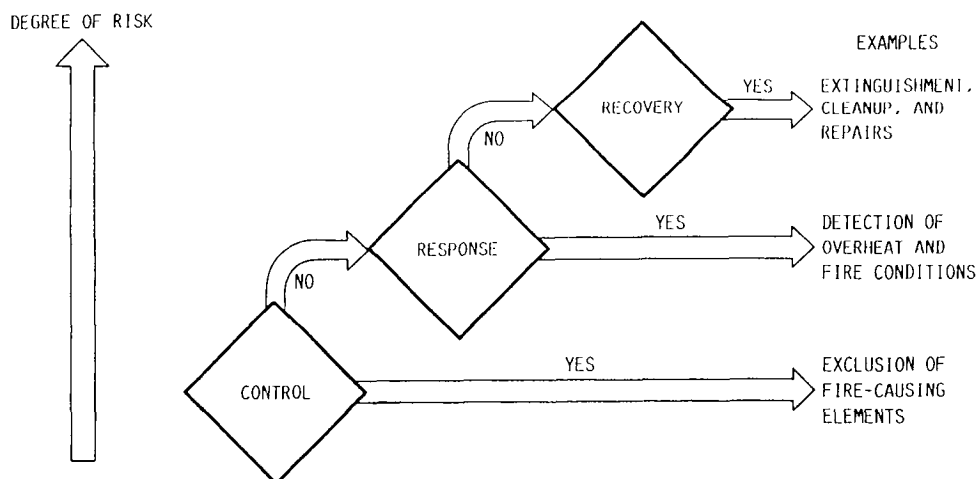


FIGURE 2. - REPRESENTATION OF SPACECRAFT FIRE SAFETY STRATEGIES.

materials and fire-safety devices but also the relationship between normal-gravity behavior and low-gravity behavior (Sacksteder, 1987).

The Earth-gravitational force acting on a mass is proportional to the amount of mass and is experienced only to the extent that the mass is prevented from falling (accelerating) freely towards the Earth. Orbiting vehicles are in a state of near-equilibrium between centrifugal and gravitational forces, and any departure from equilibrium or zero gravity results from the nonuniform imposition of gravity gradients, residual atmospheric drag, solar wind and other forces. Thus small, unattached objects within the spacecraft can experience accelerations ranging from about 10^{-7} to 10^{-4} times normal Earth gravity levels (1 g, or 9.8 m/s^2).

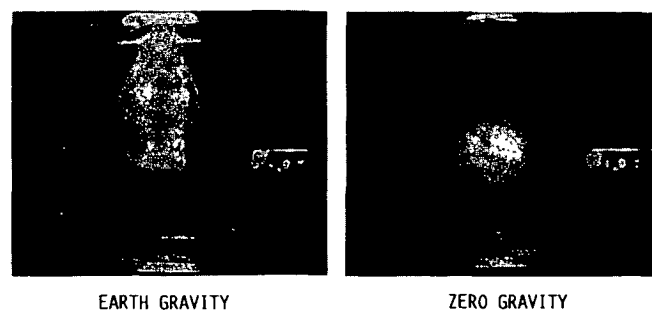
Gravitational-induced buoyancy is the result of gravitational body forces acting on a density gradient within a fluid medium, caused by temperature (primarily) and molecular-weight differences. Temperature gradients in typical flames can be quite large (1000 K/mm) and often result in the dominance of buoyant forces in normal-gravity flames. Where the gravitation levels are slight, 10^{-6} g for example, temperature gradients of this magnitude result in greatly reduced buoyancy forces, although buoyant motion may not be entirely negligible. Under these circumstances, other flow-field components emerge to influence flame spreading and flammability, namely a Stefan flow associated with the gasification of the fuel surface and any forced flow such as cabin ventilation or flow induced by fire-fighting methods. In a low-gravity spacecraft environment, low-level forced flows can inadvertently sustain the spread of flames.

Unfortunately, the use of spacecraft as a laboratory or demonstration facility for the study of reduced-gravity combustion has been limited. In fact, nearly all available flight data are derived from a series of tests conducted about 15 years ago by Kimzey (1974) in the Skylab orbiting laboratory. Most reduced-gravity testing to date has taken advantage of ground-based facilities that provide a few seconds of near free-fall conditions (Sacksteder, 1987). These facilities include drop towers, providing 2 to 5 sec of 10^{-6} g, and aircraft flying appropriate maneuvers, providing about 20 sec of 10^{-2} g (Rosenthal et al. 1987).

Flammability and Flame Spreading in Low Gravity

The flow field in the vicinity of a flame spreading over a solid fuel has a profound influence over the existence of the flame (flammability) or the rate at which the flame spreads. Because the driving forces of the flow field change dramatically from buoyancy-dominated in normal gravity to a shared influence between up to three components in low gravity, fire-protection practices developed for Earth use must be reconsidered for use in spacecraft.

Few reduced-gravity flame-spread or flammability data are available. The comparative flame-spreading tests of Andracchio and Aydelott (1970), confirmed in a different geometric configuration by Olson (1987), were performed under quiescent (no forced flow) conditions. These tests showed that, in O_2/N_2 atmospheres with up to 40 percent O_2 , flame-spread rates are consistently lower in low gravity than in normal gravity. These authors, as well as Kimzey (1974) in his Skylab experiments, also agreed in noting that, for a variety of fuel types and configurations, the flammability limits occur at higher atmospheric oxygen contents in low gravity than under normal-gravity conditions. These tests also showed that, in quiescent environments, low-gravity flames approached spherical shapes and were less luminous than their normal-gravity



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FIGURE 3. - COMPARISON OF FLAMES WITH 0.03-MM THICK PAPER SPECIMENS, FROM DROP TOWER TESTS.

counterparts (Fig. 3). Provisional conclusions from these data suggest that low heat and mass transfer rates result in less efficient, lower temperature, and reduced flame-speed combustion under space conditions, which leads to the characterization of the reduced-gravity environment as intrinsically less flammable or safer than normal gravity.

A normal-gravity flame environment is never truly quiescent, since the flame generates an upward buoyant flow due to the mass-density difference between the hot combustion gases and the surrounding atmosphere. It is interesting to note that the addition of low-velocity ventilating flows to low-gravity flames, at velocities considerably less than those associated with the corresponding normal-gravity buoyancy, greatly enhances flammability. Preliminary confirmation of this influence was obtained in drop-tower tests reported by Foutch (1987) and Foutch, et al. (1987), who showed increased low-gravity flame spread with low-velocity superimposed air flows. Support for the existence of enhanced low-gravity flammability has appeared in the discussion of Olson (1987) and the computational modeling of Chen (1986). The recent experimental efforts of Ferkul (1988) provide a quantitative demonstration of increased lower flammability limits for thin samples in an opposed-flow configuration at low gravity. Comparison of flow fields and temperature fields between normal and low-gravity flame-spreading environments is essential to establishing the desired phenomenological linkage.

Near the lower flammability limit, flames spreading in low gravity are often characterized by dim or nonluminous reaction zones that are often recognized as flames only through temperature measurements. In low-gravity tests conducted in drop-tower or airplane simulators, specimens usually burst into luminous flaming combustion upon the resumption of gravitational influence at the conclusion of the test time. Thus it may be essential to provide for incipient fire detection with attributes of flames other than visible luminosity and to provide for fire-extinguishant delivery systems that avoid low-velocity flame enhancement.

Fire-spread mechanisms not associated with the surrounding flow field arise uniquely in low gravity. In the burning of plastic materials, heat transfer to the surface induces bubble formation within the molten materials. Bursting of these bubbles releases jets of vaporized fuel into the surrounding air and may also result in the ejection of flaming particles. Trajectories of the flaming particles are not dominated by gravity (i.e., the particles do not fall to the floor), and this can result in the deposition of

ignition sources at remote locations (Olson and Sotos, 1987).

Thus, present understanding recognizes that low-gravity combustion and the potential for fire may be augmented by ventilation, particle expulsion, flame radiation, and perhaps other factors discussed elsewhere (Friedman and Sacksteder, 1987). In addition, even where flame spread is reduced in low gravity, the unusual characteristics of incipient and established fires in this environment call for pertinent knowledge and adaptive approaches in the detection and control of fires in space.

SPACECRAFT APPLICATIONS FOR FIRE DETECTION

Unsafe Conditions and Fire Signatures

The definition of a "fire" is more complex than generally assumed. Moreover, in spacecraft the presence of two fire-related conditions must be recognized, overheating and fire itself. Not only do overheating materials act as ignition sources for incipient fires, but overheating also promotes material decomposition and the off-gassing of toxic or flammable gases. Fires may initiate and propagate as luminous flames but also as nonluminous smoldering, a low-temperature combustion process. Smoldering is prone to occur in heterogeneous zones of solids and gas, such as in foams and other permeable materials found in spacecraft. Furthermore, it is possible that smoldering may be more common in low gravity, due to reduced fuel-air mixing in the absence of adequate buoyant or forced flows.

The sensing of an overheating or fire situation requires the recognition of the departure from normal conditions. These "signatures" may be in the form of radiant energy, temperature levels, gaseous species production, or solid aerosols (smoke). Fire signatures in low gravity may differ from the familiar signatures in normal-gravity fires. Less efficient flames may generate larger smoke particles and more carbon monoxide, and cooler flames may be less radiant. Thus the practical sensing of signatures in spacecraft requires at least some modification of systems established for ground and aircraft fire sensing.

Fire Detectors

Detectors respond to overheat or fire signatures through temperature level or rise, radiation, gaseous products, or aerosols (Bukowski, 1987). One class of flame detectors responds to the radiant energy emitted by flames in the infrared (IR), visible, or ultraviolet (UV) wavelength bands. The IR detector responds to the thermal emissions associated with the fire or heat source. The detector is simple and dependable and can have special circuitry to respond to flame flicker rather than continuous light from extraneous sources. The UV detector, however, responds to chemical-specie emissions (chemiluminescence) in the flame and is less likely to respond to extraneous radiation in its wavelength bands. Radiant-energy flame detectors are line-of-sight devices, but their viewing angles can be increased by several means. Figure 4 illustrates these principles with a schematic representation of a flame radiating directly to a flame-detector monitor (center), transmitting to a detector through one of several fiber-optic light tubes (left), and reflecting into a detector according to the time-dependent position of a rotating mirror (right).

Smoke detectors respond to the aerosol particles generated by overheating, smoldering, and flaming materials. These detectors are based on operating principles of photoelectric light obscuration or scattering, ionization-chamber conductance changes, or

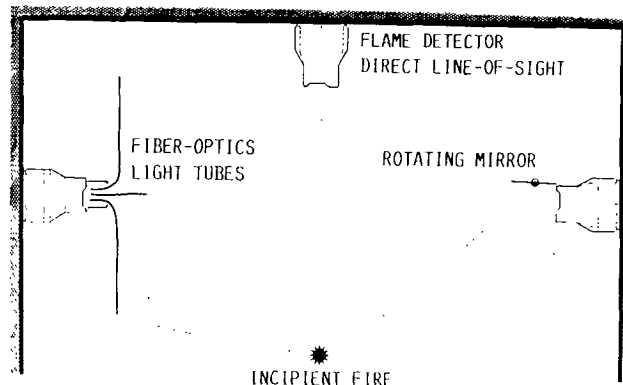


FIGURE 4. - ALTERNATIVE MONITORING CONFIGURATIONS FOR FLAME DETECTION IN SPACECRAFT.

less commonly, resistance change of a catalytic bridge element. An ionization-chamber smoke detector responds linearly in proportion to the number of particles and the particle average diameter. This type of detector retains its sensitivity over a wide range of particle sizes, and it is particularly effective for small particles, below about $0.4 \mu\text{m}$ in equivalent diameter. The photoelectric detector is more sensitive to particle size and has little response to particles with diameters less than half the wavelength of the reference beam. For the example of near-infrared beams, the minimum detectable particle size is about the order of $0.5 \mu\text{m}$. High-sensitivity photoelectric detectors can, however, respond to the small statistical distribution of larger particles even in smoke dispersions of low average-particle diameters. Typically, smoldering and incipient fires generate larger particles, but established fires tend to generate smaller particles whose average diameter decreases with time, perhaps as the transport of oxygen improves (Bukowski and Mulholland, 1978).

Overtemperature and combustion-product detectors respond to the convective transport of energy and molecular species. In space, the response of these detectors is slow unless they are fortuitously positioned at the site of the incipient fire, since the most dependable mode of signature transport by buoyant free convection is negligible in low gravity. Nevertheless, these detectors may be valuable supplements in a complete spacecraft fire-protection system, and the sensors can be designed to respond to rate of change as well as to the absolute level of their signature.

Practical Spacecraft Applications

Previous experience. In the first U.S. manned spacecraft programs, the crew functioned as fire detectors. While advanced spacecraft are too complex to relay solely on human observations, without a doubt, the alertness and discrimination of the crew will continue as an important complement to automated fire-detection systems.

The 1973-74 Skylab space station was equipped with 22 radiation flame detectors, tuned to UV at wavelengths below 270 nm , whose response was originally demonstrated in aircraft-based low-gravity tests (Linford, 1972a and 1972b). For the Shuttle, several fire detector concepts were proposed and rejected for reasons of slow response, uncertain performance in microgravity, and poor reliability, including a chemical-species detector (Krupnick, 1971), a smoke detector using a water-condensation nuclei cloud-

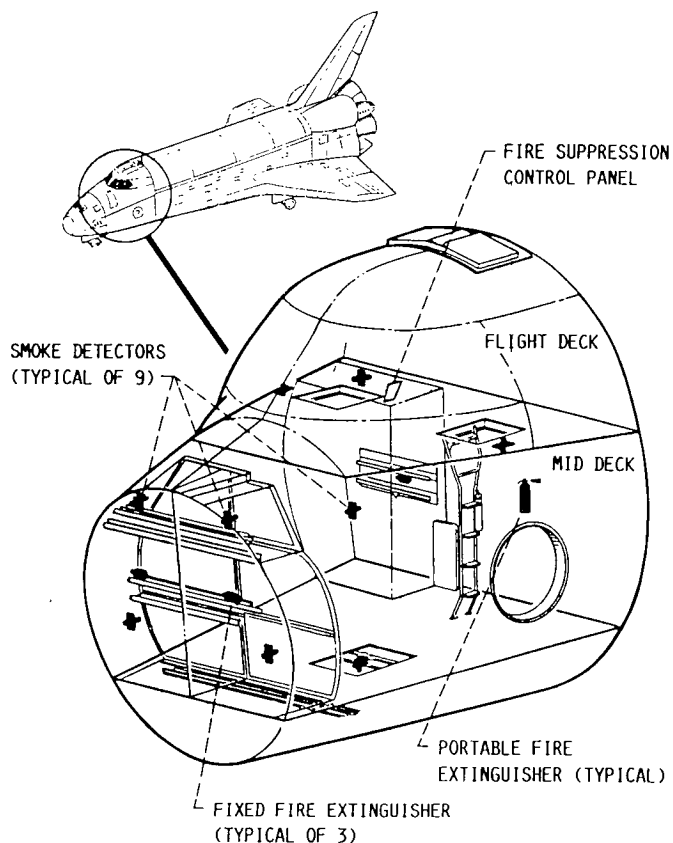


FIGURE 5. - SHUTTLE ORBITER FIRE-PROTECTION SYSTEM.

chamber principle (Bricker, 1985), and a smoke detector using a quartz-crystal microbalance bridge principle (Gibb et al. 1985). The Shuttle now employs nine ionization smoke detectors in the crew cabin and equipment bays, as shown in Fig. 5. The present smoke detector, made by the Brunswick Corp. (Report 0855-251, May 1985), is used for protection both in the Shuttle Orbiter and in the Spacelab module carried in the Shuttle payload bay. The Shuttle detector, sketched in Fig. 6, has an integral fan to ensure adequate sampling in the absence of buoyant flows (Kubicki, 1981). False alarms from ambient dust are minimized by an internal flow bypass to exclude larger particles and permit entry of small aerosol particles characteristic of smoke into the ionization chamber.

Proposals for space stations. System-safety criteria have been in place for over a decade to influence the definitions for space stations (Canetti, 1971). The formalized candidate guidelines (DG-C&W-199 in Peercy et al., 1985b) state that the fire-warning system is to be activated by smoke, fumes or heat and is to issue a warning throughout the space station, locating the fire. DeMeis (1986), quoting consultants, speculated that the most promising detector concepts for the proposed U.S. Space Station Freedom are flame detectors (IR) and smoke detectors, with coaxial-wire thermal detectors in confined areas. The thermal-detection wires are lines, used currently in aircraft engine nacelle protection, that sense both discrete overtemperature and average zone overtemperature (Waldman, 1980). These detectors operate on principles of thermistor or eutectic-salt-melting changes of resistivity with temperature or gas-law pressure changes with temperature, and they operate

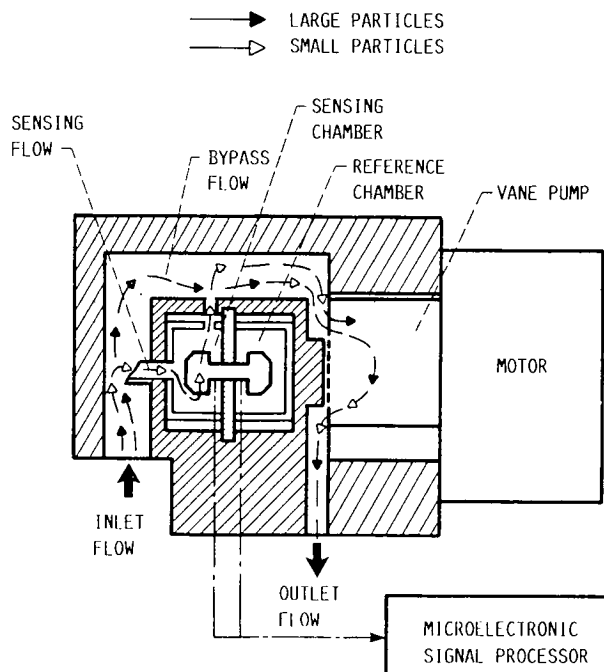


FIGURE 6. - CROSS-SECTION OF SHUTTLE IONIZATION-CHAMBER SMOKE DETECTOR.

reversibly to reset upon resumption of normal conditions after actuation.

For specific fire protection in Freedom, preliminary criteria established by the NASA Johnson Space Center call for detection of a minimum $5 \times 10^{10}/\text{m}^3$ smoke particle density and 1.5 percent/m optical obscuration. Bukowski and Mulholland (1978) estimate smoke concentrations to range from 10^{10} to 10^{16} particles/ m^3 , and the NASA guideline is an approximation of the very light smoke from an established fire. From the same source, the obscuration guideline may be estimated to correspond to a minimum smoke density of about $10 \text{ mg}/\text{m}^3$ for standard lamp-wick smoke.

Tentative fire-detection proposals for Freedom may incorporate multiple detection, for example, state-of-the-art smoke detectors, UV flame detectors, and thermal sensors within the instrument bays and their ventilation paths. General habitation areas, including airlocks, may be protected with fan-equipped smoke detectors using the Shuttle technology, flame detectors, and chemical-specie sensors for air quality.

Response and Sensitivity

Assessment of overhear or fire-detector response (time) and sensitivity (threshold signature) is only qualitative. In low gravity, it is likely that, due to slow transport rates of signatures other than electromagnetic radiation, the response time of many fire detectors will be slower than in normal gravity. Location of sensors is an important concern. Within the constraints of mass, power, and cost, it is not feasible to mount individual sensors throughout a space station. Techniques such as forced-air assistance, multiple-tube scanning, fiber optics, and rotating mirrors can maximize coverage with fewer sensors, although extensive use of coverage enhancement can make the identification of the fire site difficult.

Sensitivity of detectors also involves trade-offs in the fact that oversensitive sensors respond fre-

quently to other than fire signals (false alarms). Smoke detectors, for example, are actuated by controlled fires (cooking, smoking), dirt, construction dust, and fail-safe open circuitry. In spacecraft, false alarms are particularly undesirable since the crew must regard all detector alarms as serious indications for immediate investigation and action.

There are several approaches to augment detector sensitivity, while minimizing false alarms. Aircraft experience promotes the use of cross-zoned systems, where detectors, preferably of differing generic configurations, monitor overlapping zones (Mniszewski et al. 1983). Logic circuitry requires multiple actuation ("AND" logic) before an alarm is activated. Another approach is to set sensing elements at two levels of response, "WARNING" and "DANGER", for example. In some battle tanks, a two-sensor cross-zone logic uses manual selectors for normal and combat situations. The normal condition requires the actuation of both sensors for activation ("AND" logic); the combat condition responds to a single actuation ("OR" logic). This technique may be used in spacecraft modules attended only during working (day) hours, with "AND" logic in the day, "OR" logic in the night.

Crew Decisions

The preferred reaction to an overheat or fire alarm should be simple, manual, and rehearsed. On the other hand, in unattended or inaccessible spacecraft locations, automated fire protection incorporating alarms, equipment shut off, and extinguishant discharge is essential. An incipient fire may require nothing more than localized isolation and cooling, but a continuing fire would require use of more active fire-extinguishing procedures. A catastrophic fire may require partial or complete crew escape, isolation of an entire zone, and complex fire-fighting methods. The safety design guidelines for space stations (Peercy et al. 1985b) propose common-sense preparations for the crew, where overall health and safety responsibilities are assigned to a specific crew member, with alternates (the fire marshals).

For long-duration, permanent space operations, periodic testing and calibration of detectors should be scheduled, beyond the conventional continuity checks of circuitry. Bukowski and Mulholland (1978) discuss aerosol generators to calibrate smoke detectors, but the low-gravity calibration systems for radiant, heat, or smoke signatures have yet to be invented.

FIRE FIGHTING IN SPACECRAFT

Inerting and "Fire-Safe" Atmospheres

Exclusion of oxygen removes one element of the "fire triangle" (Fig. 1). The exclusion can be continuous, such as in the maintenance of inert atmospheres in uninhabited compartments, or it can be temporary, such as in fire extinguishment by inert-gas flooding. Nitrogen inerting for protection of fuel tanks in military aircraft has been studied during the past decade (Waldman, 1980; Mniszewski et al. 1983). A promising technique investigated by Desmarais and Tolle (1983), Desmarais et al. (1983) generates the inert gas through oxygen removal from atmospheric air by methods called onboard inert-gas generating systems (OBIGGS), using either a molecular-sieve adsorbent or a permeable membrane. This inerting atmosphere need not be composed entirely of nitrogen. The OBIGGS separation process is simplified by retaining as much as 6 percent or, for some applications, even 9-percent residual oxygen in the fire-safe atmosphere. The separated oxygen component, vented overboard in aircraft, would be recycled in spacecraft

counterparts. Other inerting agents have chemical-extinguishing properties. Halon 1301, an extinguishant discussed later in this section, effectively prevents flammability in concentrations typically no greater than 6 percent.

Inerting need not be confined to uninhabited spacecraft compartments. For example, Carhart (1987) has urged the investigation of reduced-oxygen atmospheres for spacecraft habitation zones, based on favorable submarine test experience. It is well established that atmospheric compositions with an oxygen partial pressure adequate for life support may have an oxygen fraction (because of the inert diluent) insufficient to support combustion (McAlevy and Magee, 1967). Lowering the oxygen concentration at a fixed partial pressure of oxygen by nitrogen flooding is the proposed technique for emergency fire suppression in submarines. Gann et al. (1978) reported on the fire-control effectiveness of this method, and Dressler et al. (1977) reported on the respiratory safety, based on animal tests. A permanent, fire-safe atmosphere in a spacecraft more likely would have a standard (101.3 kPa) total pressure but a reduced oxygen content. The review of Horrigan (1979) noted that oxygen partial pressures as low as 16.5 kPa, equivalent to those of 1800 m (6000 ft) altitudes, may be acceptable for long-term human activities. More unconventional is the recommendation of Huggett (1973) on the use of a breathable atmosphere in which at least part of the nitrogen is replaced by a high molar-heat-capacity diluent gas (sulfur hexafluoride, for example). Despite the scientific backing for fire-safe breathing atmospheres, their adoption in the next generation of spacecraft is doubtful. Human tests must be performed to assure that the substitute diluents or the reduced oxygen contents would not have long-term effects on human efficiency and performance, at the very least. Some of the proposed options involve considerable spacecraft structural, gas handling, and metering changes. Most important, many material, fluid, and biological projects planned for advanced spacecraft assume the presence of "air," and adaptations to the unconventional atmospheres may be impractical.

Fire Extinguishment in Space

Previous experience. In space, an ideal extinguishant should be effective (minimum quantity necessary to extinguish fires), nontoxic in its original state and by-products, noncorrosive, and readily removable by the spacecraft cleanup or environmental-control systems. All types of extinguishants, including powders, liquids, foams, and gases, may merit some consideration for space, but no one type of extinguishant can meet all of the desirable criteria.

In the early human space missions, the metering water dispenser was designed as an alternative fire extinguisher (McAllister, 1972) although Skylab had extinguishers that discharged foam produced by an aqueous gel. At present, the Shuttle is equipped with three fixed and four portable fire extinguishers, discharging Halon 1301 (trifluorobromomethane), sized to produce an extinguishant concentration of 6 to 7 percent (Figs. 5 and 7). These extinguishment techniques owe much to methods evolved for aircraft flight and ground protection (Desmarais and Tolle, 1983b; Kuchta and Clodfelter, 1985), where effective systems use Halon and aqueous film-forming foam (AFFF) extinguishants, among other agents.

Halon 1301 is a chemical extinguishant, inhibiting the combustion reactions; and it is very effective on surface fires and, as noted previously, in atmospheric inerting. Tests by Haggard (unpublished NASA

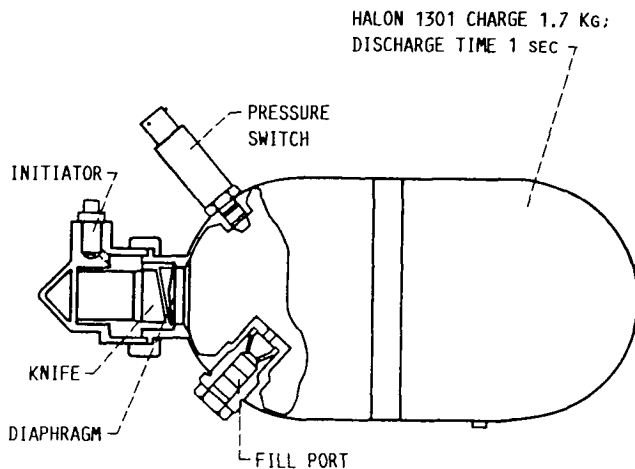


FIGURE 7. - SKETCH OF SHUTTLE FIXED-POSITION HALON 1301 FIRE EXTINGUISHER.

Lewis data) and Ronney (1985) have shown a corresponding effectiveness in low gravity. In deep-seated fires, and possibly in smoldering fires, where extinguishment proceeds best through cooling and oxygen exclusion, Halon 1301 is less effective. (In fact, the National Fire Code, NFPA Standard 12A, paragraph A-2-4, defines a deep-seated fire as one that cannot be extinguished by 5 percent Halon 1301 within 10 min of application.) Ground usage of Halon 1301 is an environmental problem, because the escaped fluorocarbon is known to affect the stratospheric ozone layer. There are also drawbacks to Halon 1301 usage in spacecraft (deRis, 1987). Animal tests have demonstrated that leakage of the unreacted extinguishant is harmless for short exposures, but the reacted extinguishant generates hydrogen halides, HBr and HF. The question of the toxic and corrosive harm from the Halon 1301 products following a fire and how the products can be removed from the spacecraft atmosphere remains to be solved. In the Shuttle, Halon 1301 use is justified by the requirement that a mission is return to Earth as quickly as possible after extinguishant discharge (Kubicki, 1981).

Proposals for space stations. Carbon dioxide is a leading candidate for the primary extinguishant in the proposed U.S. Space Station Freedom. Carbon dioxide systems are simple, reliable, and cost effective, and excess extinguishant is removable through the spacecraft environmental controls. The disadvantage of carbon dioxide is that, for established fires, concentrations of this agent are required that pose toxic and asphyxiant hazards for humans. Other extinguishants have been proposed, other than the state-of-the-art Halon 1301, whose deficiencies have just been discussed. DeMeis (1986) calls attention to deionized water, obviously an effective extinguishant, removable by the spacecraft environmental controls. The unknown factor for water is in the proper management of a spray-delivery system that will work in space. Another suggestion is AFFF. Foams depend on their ability to float and blanket the burning surface. In low gravity, there is negligible buoyancy, and demonstration tests will be required to show adherence of the foam to the burning surface.

Venting. A space-station candidate safety guideline (DG-ECS-008, in Percy and Raasch, 1985b) provides for automatic venting of habitable volumes in the event of a fire or overpressure, to reduce the total pressure. Continued venting to the vacuum of

space offers an option for ultimate control of difficult fires by removal of oxygen. This technique of vacuum venting was investigated on a small scale by Kimzey (1974) in the Skylab flammability tests. The interesting observation was that the venting at first intensified the flame through forced convection before extinguishing the fire. Thus, large-scale venting must be carefully planned. Rapid venting can cause structural damage, but slow venting may temporarily prolong and increase the burning intensity.

Nevertheless, venting is a plausible last resort for fires uncontrollable by primary extinguishment techniques. In Freedom, a decision would be made quickly to evacuate the fire-fighting crew to a haven (a designated module or node) and actuate the venting. After the fire is apparently extinguished, the crew would appraise the conditions in the affected volume from the remote location. Rehabilitation and atmospheric reconstitution of the affected zone are aided by the fact that complete venting is not necessary to control fires, and the module may retain a substantial fraction of its original atmosphere at all times.

Automation and special problems. The Shuttle extinguishing system is entirely manual. Discharge of the fixed extinguishers is a two-step process, where the crew first actuate an "armed" switch then the "discharge" pushbutton. For more complex spacecraft, some automatic systems must be included. For active, automatic fire extinguishing systems, selection of a detector and recognition system with the proper level of sensitivity and discrimination is critical. The discharge of extinguishant upon a false alarm in an unattended compartment could destroy valuable projects.

Two unusual situations in space may further tax the fire-extinguishing systems. First, smoldering may be the most probable fire-related event, and these nonluminous fires may be as difficult to extinguish effectively and quickly as they are to detect. Second, particle clouds or aerosols, resulting from spills or other incidents, are persistent and nondispersing in space. Fires in these heterogeneous systems are dangerous in that they are well supplied with oxygen, propagate quickly, and are difficult to extinguish.

Atmospheric Contamination and Equipment Damage

In spacecraft, a considerable portion of the effort in combating fires may take place after the fire is extinguished. Cleanup, repairs, and medical attention, as necessary, while patterned after corresponding normal-gravity procedures, may involve unique activities in space. Of these post-fire activities, only the subject of atmospheric contamination lies within the scope of this report.

Toxic combustion-product gases, rather than burns, are responsible for most human casualties from fires. Carbon monoxide is the principal lethal agent in fire products, but plastics may also generate cyanides, chlorides, fluorides, and other toxic gases. The human response to contaminants depends on both the concentration and the duration of exposure (Kaplan, 1979). Acceptable limits derived from normal-gravity tests may not apply to space. Reduced convective transport of oxygen affects the temperature and completeness of combustion, altering the nature and concentration of combustion products. A space-station candidate guideline (DG-HMS-103, in Percy and Raasch, 1985b) urges the establishment of contaminant threshold limit values for space, presumably including those generated by fires. Effects of contamination may also be cumulative or synergistic. For example, a few percent of low-

toxicity CO₂ greatly increases the lethality of carbon monoxide (Babrauskas, et al. 1986). In space, the life-support atmosphere may be contaminated not only by fire by-products but also by those from the extinguishant, for example, the hydrogen halides generated from Halon 1301. In fact, the choice of advanced spacecraft extinguishing systems may be dictated as much by the ease of cleanup as by the efficiency of extinguishment.

In addition to the immediate effects requiring post-fire attentions, there are delayed effects, primarily corrosion from exposure to combustion and extinguishant products. Some attention has been given to the particular problems from the halide products of Halon 1301 extinguishment. A review of Youngblood (1988), citing the Air Force tests by Reichelt et al. (1982) and other unpublished works, noted that exposure to Halon 1301 fire-extinguishment products had no immediate adverse effects on the performance of electronic components otherwise protected from the heat of a fire. Smoke from burning polyvinyl chloride cable insulation, however, resulted in severe corrosion. Since these observations are based on limited, normal-gravity tests, there is a strong need for further study of potential corrosion under long-duration, low-gravity conditions.

SPACE STATION FIRE-SAFETY ISSUES

The Space Station Freedom is planned as a multi-component community assembled and maintained in a low Earth orbit. The purposes of Freedom include tending independent unmanned orbiters, launching unmanned and (eventually) manned space probes, and maintaining and recovering other Earth satellites. Above all, Freedom space station will be a laboratory and workshop for scientific and industrial operations that exploit the advantages of the extraterrestrial location, including the microgravity environment and the access to near-perfect vacuum. The scientific and operating crew will reach and return from Freedom by Shuttle flights, and the crew will remain for long-duration assignments. Thus, the plans for Freedom and its risk management must recognize that there will be a range of housekeeping and recreational activities onboard, as well as scientific and technological activities. Responses to fire control must assume that detection, extinguishment, atmospheric decontamination, and a moderate portion of repair and medical treatment capabilities are all provided by supplies and systems within the space station.

The present concept of the Space Station Freedom laboratory, supply, and habitation zones is that of a "ladder" arrangement of modules and nodes (Fig. 8). This configuration assures the evacuation from a damaged or fire-stricken module and its isolation. The crew may retreat to any portion of the space station without traversing through the affected volume (DeMeis, 1986). This safety concept of a "haven" and the role of the crew in remote management of resources in an emergency is an essential factor in the present operational planning for Freedom.

Needs and concerns for space-station fire safety can be approached by a division into categories of those of near-term and of far-term significance. The near-term issues are those whose resolution is influential in the designs for Freedom and its family of advanced spacecraft. Far-term issues, in contrast, are those whose resolution may be beyond present capabilities, perhaps requiring testing onboard the operational Freedom space station itself.

The near-term issues encompass many of the spacecraft fire-safety unknowns and problems already dis-

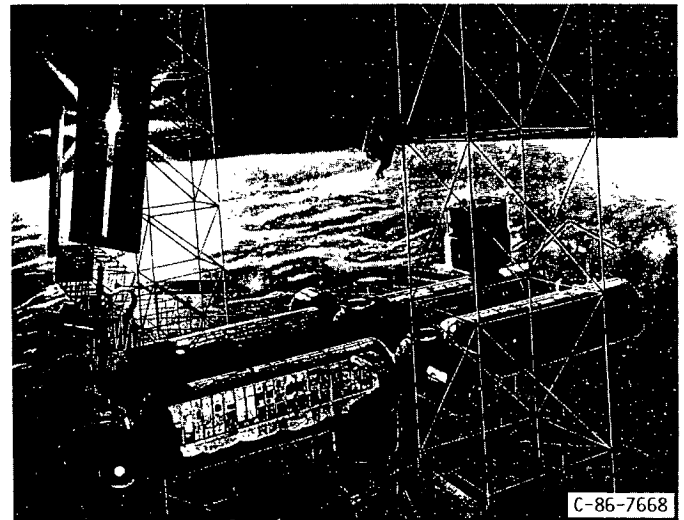


FIGURE 8. - ARTIST'S SKETCH OF SPACE STATION, SHOWING MODULES AND NODE CONSTRUCTION.

cussed in this paper. A summary of the important issues, based upon the greatly appreciated reviews and suggestions of M. Cole of NASA Johnson Space Center and F. Clarke of Benjamin/Clarke Associates, follows:

(1) Understanding combustion in low gravity, including energy release and product evolution, for eventual prediction of fire signatures and combustion-product composition.

(2) Measurement of ignition and flame spread for solid materials in low gravity, for development of material acceptance standards applicable to the space environment.

(3) Investigation of aerosol characteristics in low gravity, to contribute to the understanding of flammability from spills, line breaks, and other dispersions in space.

(4) Development of fire-detection techniques and systems, suitable for long-term operation in spacecraft, with desirable sensitivity, response, and calibration attributes.

(5) Development of a set of fire-extinguishment techniques that are effective under all expected spacecraft operational scenarios.

(6) Application of artificial intelligence and communication codes to establish response guidelines for spacecraft fire detection.

(7) Development of environmental controls for postfire cleanup of combustion and extinguishment products to protect the spacecraft crew and sensitive equipment.

Certain far-term studies that are valuable in the utilization and experimental-facility planning for Freedom are also worth noting. The Freedom space station will offer an extremely attractive environment for low-gravity fire-safety testing, since its laboratories promise exposure to microgravity without time restrictions and generous power, mass, volume, and diagnostic accommodations. One proposed microgravity-combustion facility for Freedom that is readily adaptable for fire-safety investigations is illustrated in Fig. 9 (Youngblood and Seiser, 1988, Youngblood, 1988). The facility is a flow loop, designed to fit into multiple standard-rack locations in a space-station laboratory module. The primary function of this facility is the investigation of material flammability under low-gravity, variable forced-flow condi-

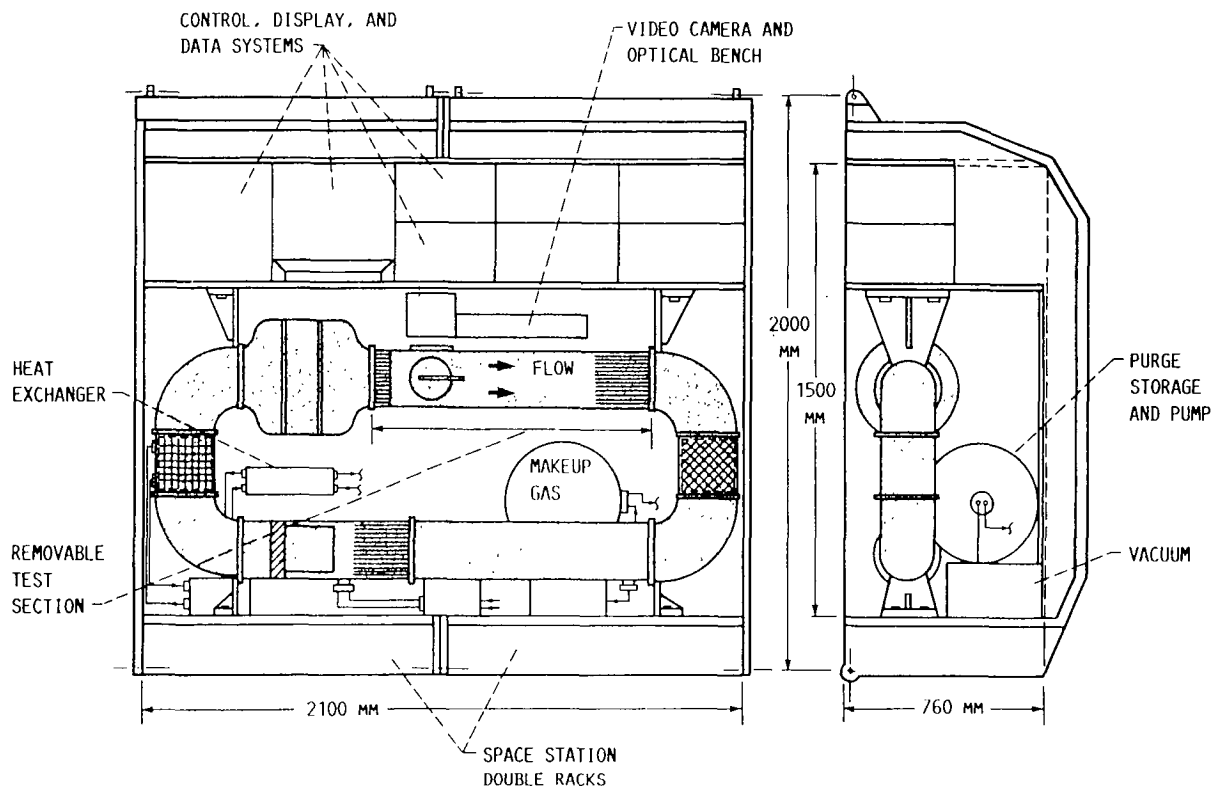


FIGURE 9. - FLOW-LOOP FACILITY PROPOSED FOR SPACE STATION FIRE-SAFETY STUDIES.

tions, a realistic representative of the spacecraft environment. Eventually, such a facility could contain installations for standardized material evaluations, detector calibrations, and other testing, both routine and research. The facility may operate continuously as a flow loop, except for minor oxygen makeup and venting as combustion products accumulate. Freedom would provide certain common utilities and instrumentation and some degree of crew involvement to supplement the self-contained and automated features shown.

CONCLUDING REMARKS

This paper has presented a review of present knowledge and applications underlying fire-safety planning for advanced spacecraft. The purpose of the review is to establish a risk-management basis for future spacecraft, particularly a space station which is a complex, permanent space structure. Minimization of fire risks may impose excessive demands on structures and operations, increasing complexity and costs, and above all, limiting the usefulness of a space station. Thus the objective of spacecraft fire-safety management is a risk optimization based on a trade-off of practical fire-safety approaches against small but tolerable risks. The application of this philosophy to orbiting spacecraft involves the interaction of strategies of control of fire-causing elements, response to incipient fires, and recovery from fire damage as necessary. The critical needs to promote this fire-safety program to meet the needs of space stations, such as Freedom, can be met through a combination of fundamental research, practical application, skillful adaptation of established techniques from aircraft and submarines, and necessary testing and demonstrations in low gravity.

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16. Abstract Practical risk management for present and future spacecraft, including space stations, involves the optimization of residual risks balanced by the spacecraft operational, technological, and economic limitations. Spacecraft fire safety is approached through three strategies, in order of risk: (1) control of fire-causing elements, through exclusion of flammable materials for example, (2) response to incipient fires through detection and alarm, and (3) recovery of normal conditions through extinguishment and cleanup. Present understanding of combustion in low gravity is that, compared to normal-gravity behavior, fire hazards may be reduced by the absence of buoyant gas flows yet at the same time increased by ventilation flows and hot particle expulsion. This paper discusses the application of low-gravity combustion knowledge and appropriate aircraft analogies to fire detection, fire fighting and fire-safety decisions for eventual fire-risk management and optimization in the spacecraft.					
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